Do Gluons Carry Proton Spin? –
toward resolving the "Spin Crisis"

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Outline

Why Spin

    Role of the Spin

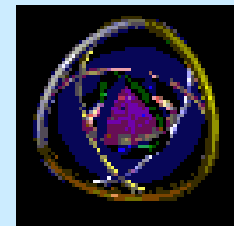   Proton Spin Structure and Spin Crisis

Why Gluons

    Role of Gluons

    Probing Gluon Spin Contribution

What's next

Spin

Fundamental Concept in Physics

Appears in all levels: from galaxies to elementary particles

Spin

Spin is a fundamental quantum mechanical property of elementary particles (like mass, charge)

- ➢ Carries the same mathematical meaning as angular momentum (rotational motion in classical mechanics)
- ➢ Spin in quantum mechanics is quantized in units of Planck's constant h, and can be either integer (0, 1, 2 etc) or half-integer (1/2, 3/2 etc);
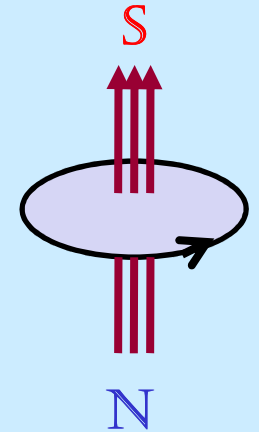- ➢ **Proton**, **neutron** and **electron** are spin-1/2 particles

Spin plays central role in theory of strong interaction, Quantum Chromodynamics (**QCD**)

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Spin and particle internal structure

Associated with particle spin is magnetic moment
(like rotating electrically charged body)

S

$$\mu = g\,\frac{e}{2m}\,S$$

e – electric charge
m – mass
S - spin

N

From quantum theory (Dirac equation):
g~2 for elementary (point-like) ½-spin particle
Confirmed in the experiment for **electrons** and **muons**

Triumph of quantum theory!

$$\mu_p = (2.79)\cdot 2\cdot\frac{e}{2M}\,S \equiv 2.79\mu_N$$

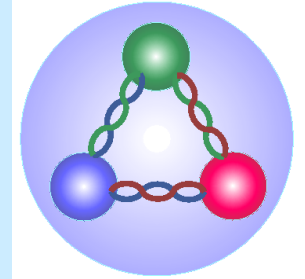$$\mu_n = (-1.91)\cdot 2\cdot\frac{e}{2M}\,S \equiv -1.91\mu_N$$

Proton: g ≠ 2 !

Neutron: non-zero magnetic moment
for electrically neutral particle!

Compositeness of proton and neutron!

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Nucleon Spin

Nucleons $\equiv$ protons and neutrons

Quark Model: proton and neutron are made of three quarks

$p = (uud)$
$n = (ddu)$

	Charge	Spin
u	+2/3e	1/2
d	-1/3e	1/2

$\rightarrow$

	Charge	Spin
p	+e	1/2
n	0	1/2

Compute proton (neutron) magnetic moment in terms of quark magnetic moments

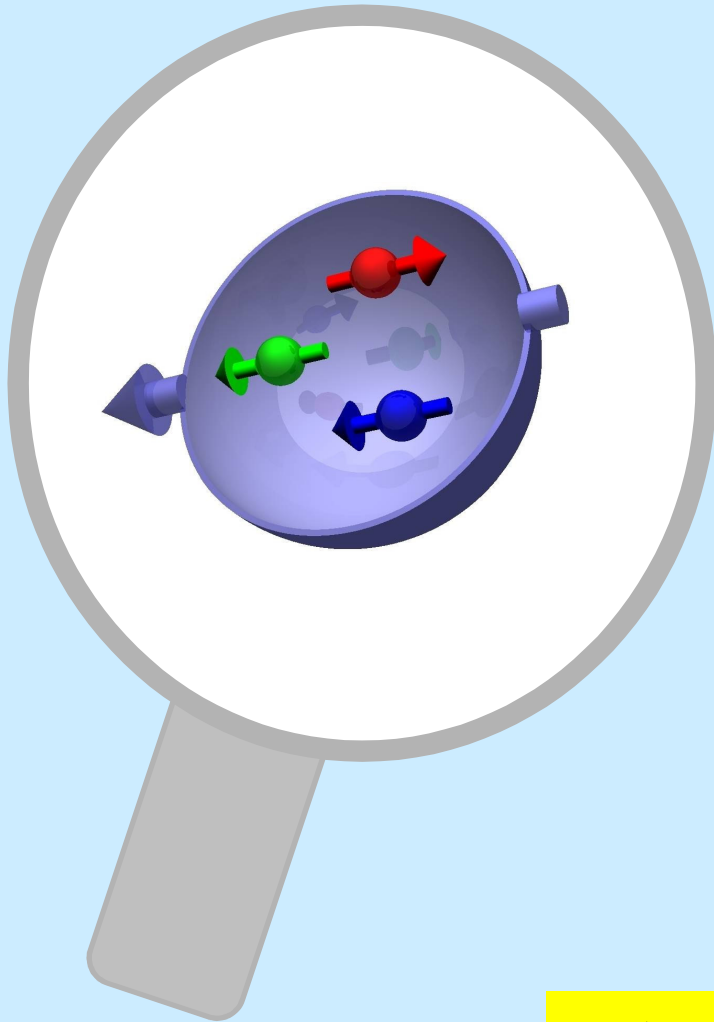$$\mu_p = \mu_u$$

$$\mu_n = -\frac{2}{3}\mu_u$$

Measurements:

$$\left.\begin{array}{l} \mu_p = 2.79\mu_N \\ \\ \mu_n = -1.91\mu_N \end{array}\right\} \Rightarrow \frac{\mu_n}{\mu_p} \approx -\frac{2}{3}$$

In very good agreement with experimental data !

Another triumph?
So, quarks carry nucleon spin ?!

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… Proton Spin Crisis

EMC (CERN) experiment:
Deep Inelastic Scattering (DIS) of high
energy polarized muons on polarized protons

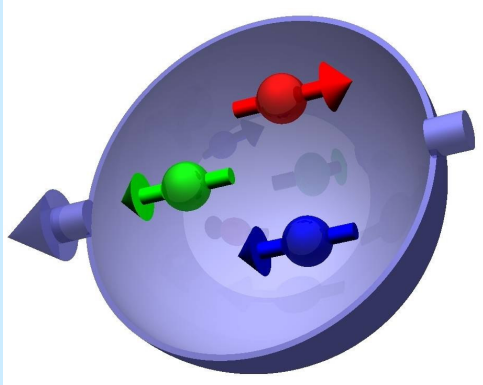Quark (and anti-quark) contribution
to proton spin is small:

$$\Delta\Sigma = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\ \%$$

Nucl. Phys. B328, 1-35 (1989) – one of the
most cited papers! >1200 citations

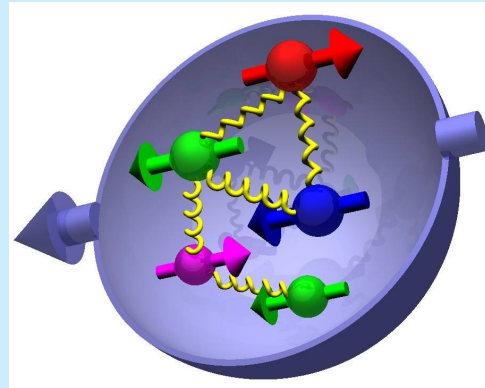What carries the proton spin ?!

Proton Spin Structure

Partons $\equiv$ (anti)quarks and gluons

Naïve quark model
(only **valence quarks**):

$$\frac{1}{2} = \frac{1}{2}\left(\Delta u + \Delta d\right)$$

Quark contribution
is small
$\Rightarrow$ Spin Crisis
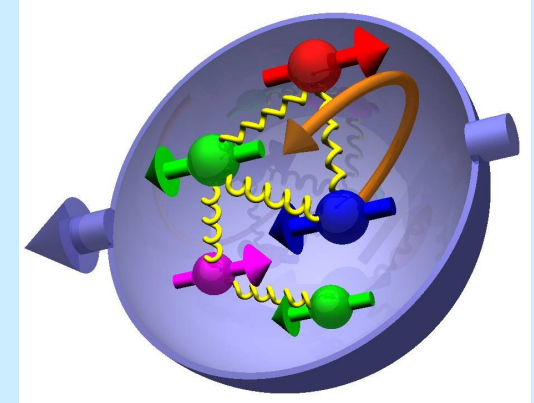
+ **gluons**
    strong force carrier
+ **sea quarks**
    Quantum mechanical
    fluctuations $g \to q\bar{q}$

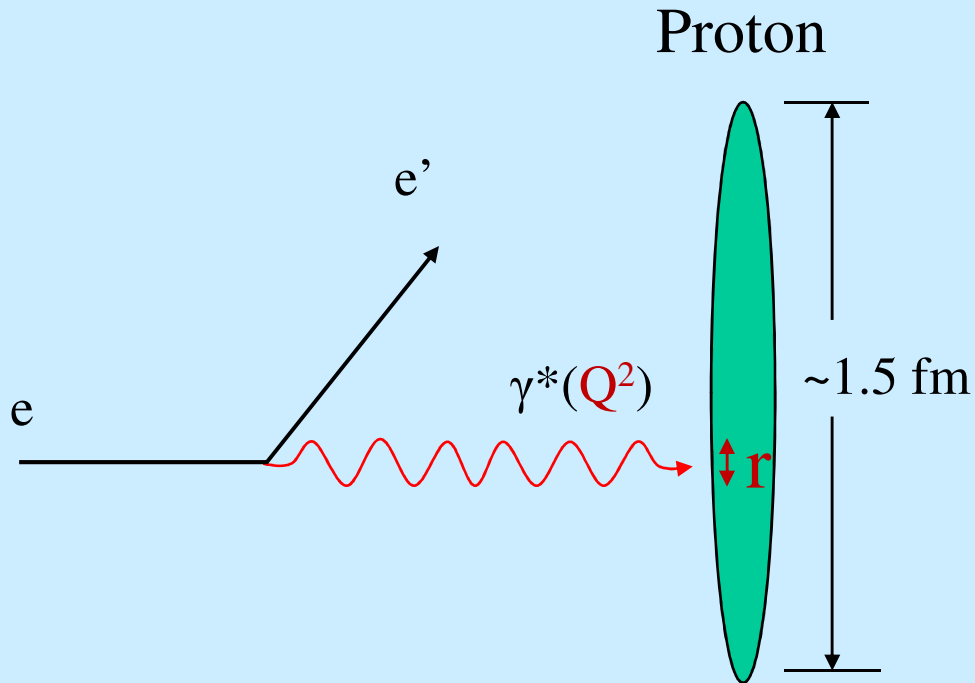$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta\bar{q}\right) + \Delta G$$

For complete description
include parton **orbital
angular momentum** L_z:

$$\frac{1}{2} = \frac{1}{2}\left(\Delta q + \Delta\bar{q}\right) + \Delta G + L_z$$

Determination of ΔG and $\Delta\bar{q}$ is the main goal of
the RHIC spin program

Probing Proton Structure

Proton
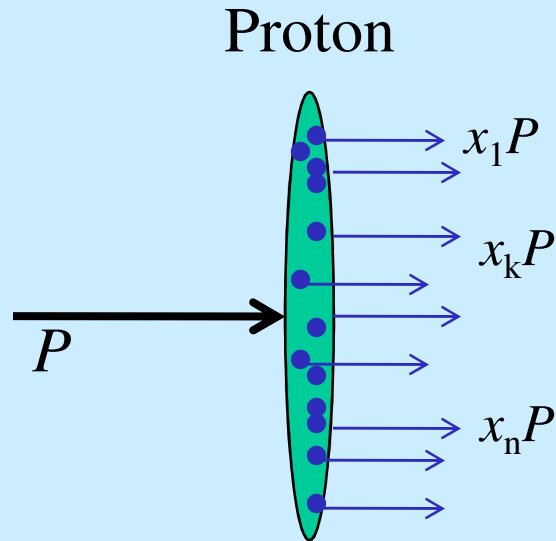
e'

e

$\gamma^*(Q^2)$

~1.5 fm

r

Virtuality (4-momentum transfer^2) Q^2 gives the distance scale r at which the proton is probed.

$$r \approx hc/Q = 0.2 \text{fm}/Q[\text{GeV}]$$

HERA ep collider: $r_{min} \approx 1/1000$ proton diameter

$E_e = 27.5$ GeV, $E_p = 920$ GeV

Parton Distribution Functions (PDF)
or parton densities

Proton

x_k – fraction of proton momentum
carried by parton k; so $0 < x_k < 1$

Momentum Sum Rule: $\sum_k x_k = 1$

(Gluons carry ~1/2 of the proton momentum)

$f(x)$ - Parton Distribution Function (PDF): probability for a parton to carry fraction x of the proton momentum

Higher probe Q^2 – better resolution
    Start resolving more virtual (short life) stuff, sea quarks and gluons with lower x

So, different Q^2 probes see proton structure differently: $f(x) \rightarrow f(x,Q^2)$

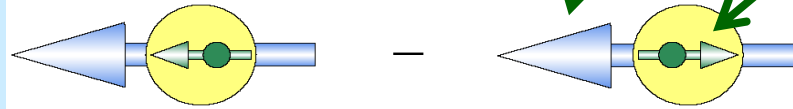Once $f(x,Q^2)$ is known at some Q_0^2 scale, it can be calculated for any other Q^2

Polarized PDF

$q = u,d,s \ldots$

Proton spin   Quark spin

Quarks

helicity (longitudinal spin) distribution
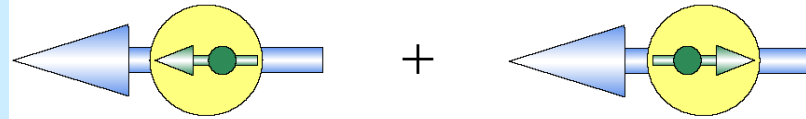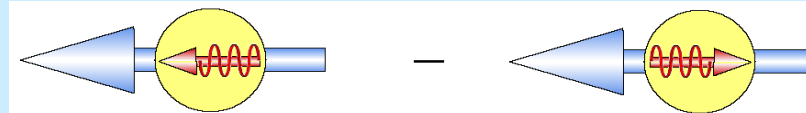
$$\Delta q(x,Q^2) = $$

unpolarised distribution

$$q(x,Q^2) = $$

Gluons

helicity (longitudinal spin) distribution
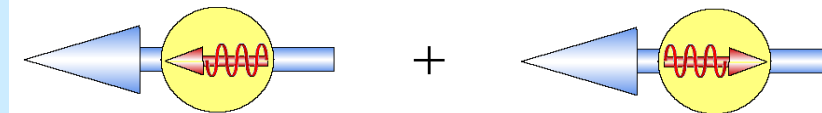
$$\Delta g(x,Q^2) = $$

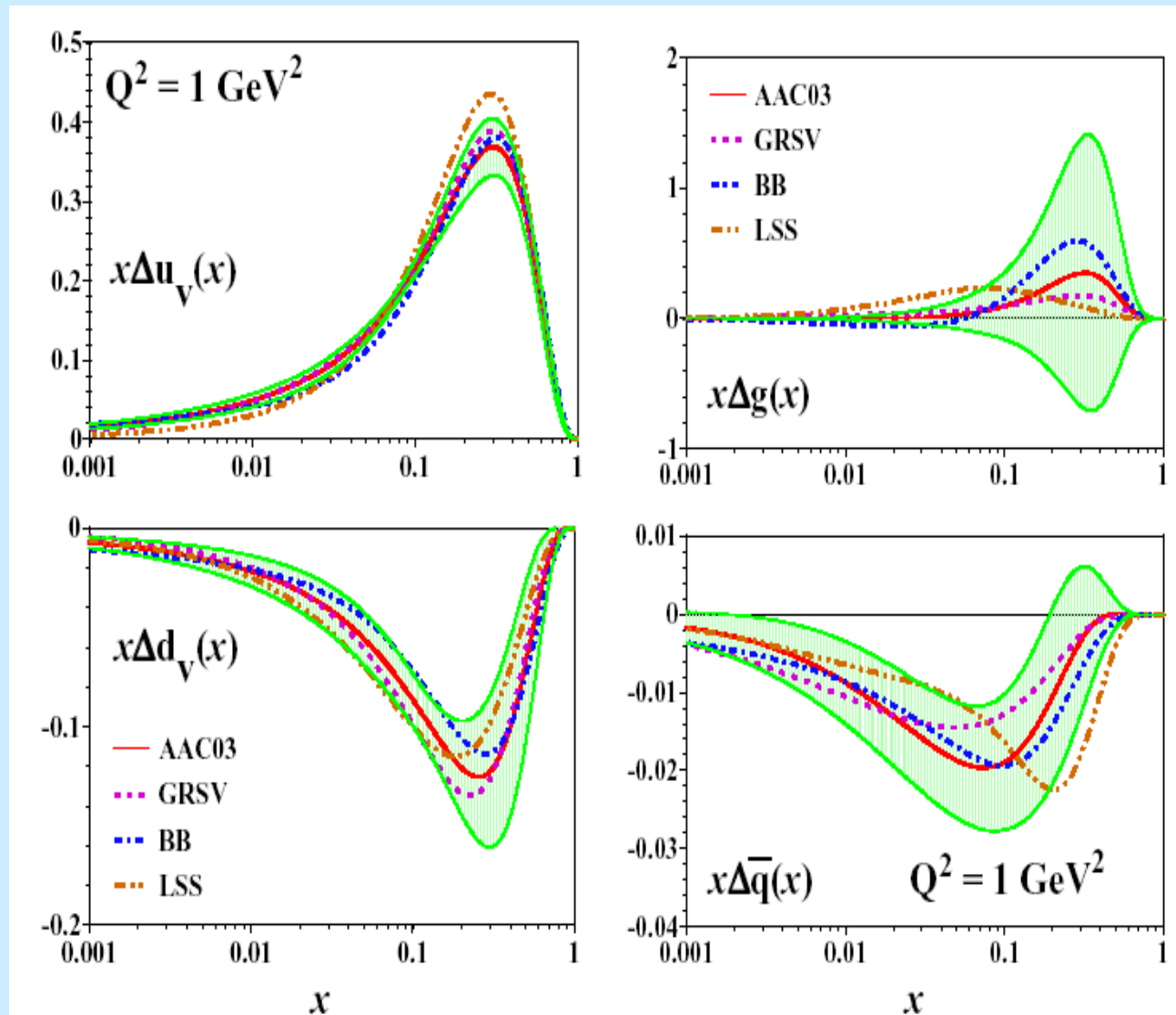unpolarised distribution

$$g(x,Q^2) = $$

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Polarized PDF from DIS
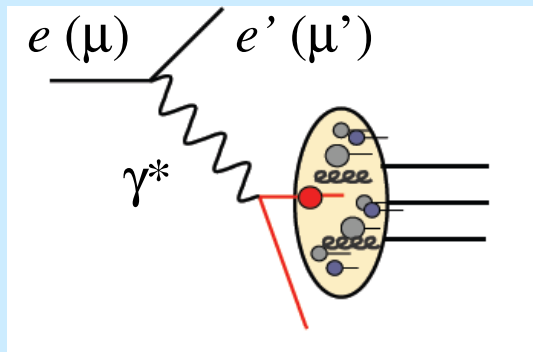
Asymmetry Analysis Collaboration
M. Hirai, S. Kumano and N. Saito, PRD69, 054021 (2004)

- Valence distributions well determined

- Sea Distribution poorly constrained

- Gluon very poorly constrained: can be either positive, 0, negative!

From inclusive polarized DIS …

✓ Only information about input and scattered lepton (e, μ) is recorded

 x and Q^2 reconstructed from kinematics

✓ Does not distinguish quark and antiquark

 Scattering ~charge^2

✓ Do not have direct access to gluon

 Probe it through scaling violation (Q^2 dependence of quark PDFs) - with very poor precision currently

Change in Δq vs Q^2 is defined by the probability that quark and gluon radiate quark

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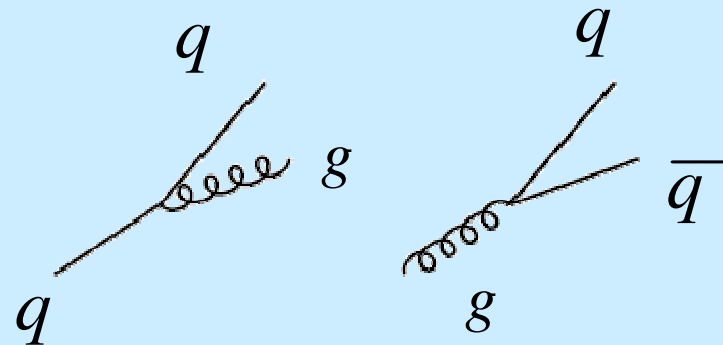
… To polarized pp collider
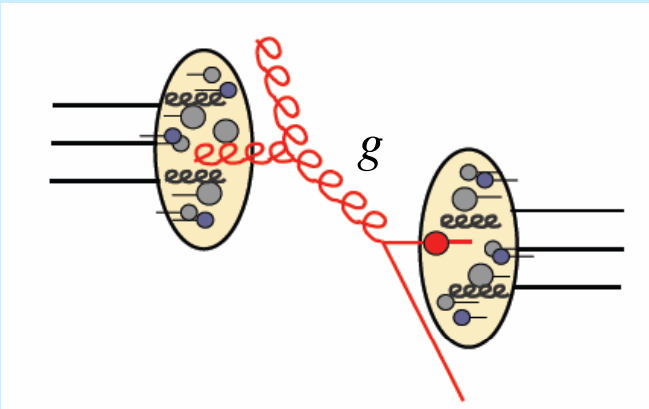
- ✓ Probes gluon directly
- ✓ Higher energies $\Rightarrow$ clean pQCD interpretation

  100 GeV protons on fixed target: $\sqrt{s}$=14 GeV

  100 GeV + 100 GeV protons at a collider: $\sqrt{s}$=200 GeV
- ✓ Elegant way to explore quark and anti-quark polarizations through W production

Polarized Gluon Distribution Measurements (ΔG):

✓ Use a variety of probes

    Access to different gluon momentum fraction x

    Different probes – different systematics

✓ Use different beam energies

    Access to different gluon momentum fraction x

RHIC as polarized proton collider

Absolute Polarimeter (H jet)

RHIC pC Polarimeters

BRAHMS & PP2PP ($\vec{p}$)

$$L_{max} = 2 \times 10^{32}\ s^{-1}cm^{-2}$$

$$70\%\ \text{Polarizati on}$$

$$50 < \sqrt{s} < 500\ GeV$$

PHENIX ($\vec{p}$)

STAR ($\vec{p}$)

Siberian Snakes

Spin Rotators

2×10^{11} Pol. Protons / Bunch

$\varepsilon = 20\ \pi$ mm mrad

Partial Siberian Snake

LINAC

BOOSTER

Pol. Proton Source
500 μA, 300 μs

AGS

200 MeV Polarimeter

AGS Internal Polarimeter

Rf Dipoles

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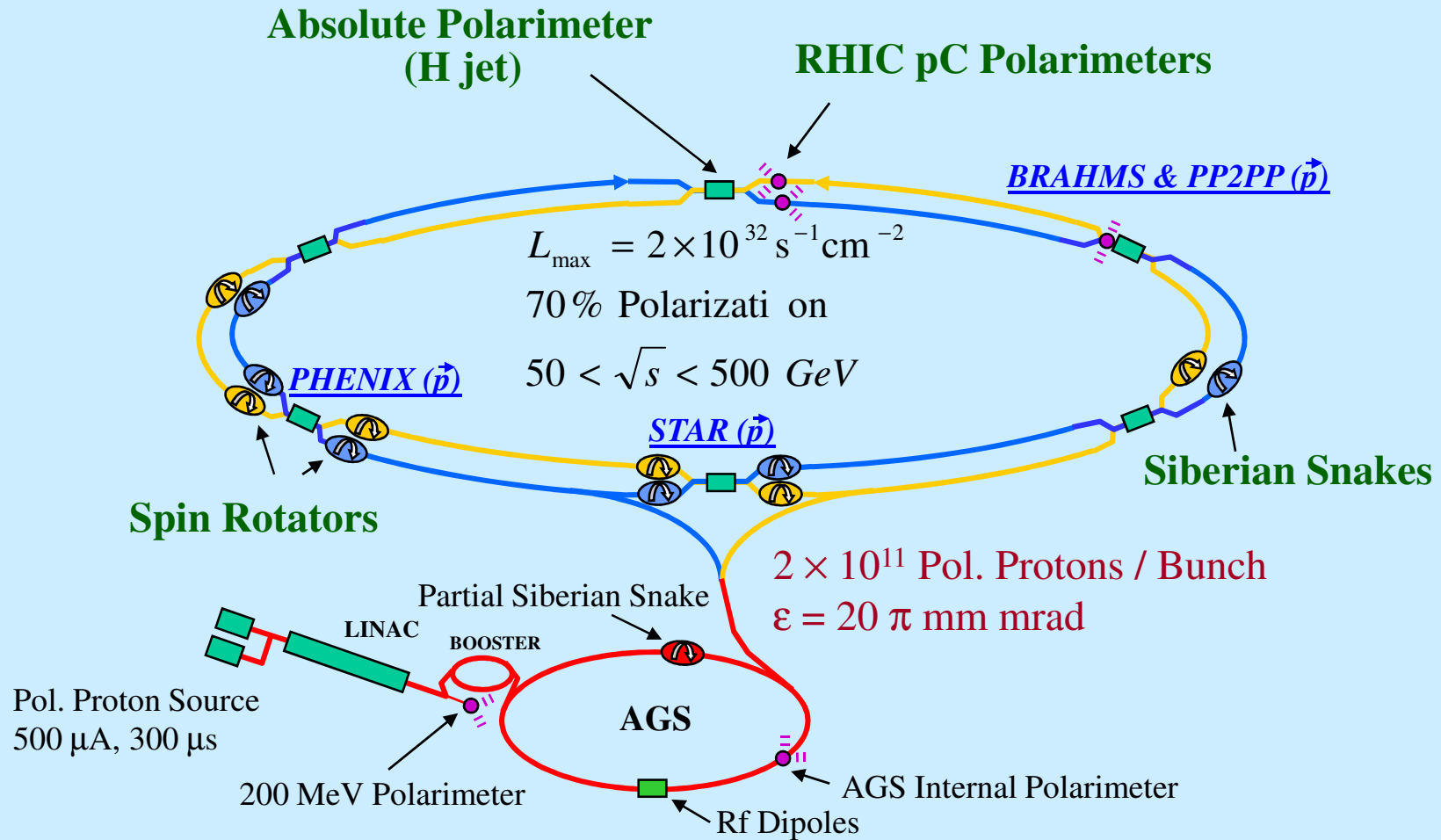
RHIC Progress

Parameter	Unit	2002	2003	2004	2005	2006
No. of Bunches	--	55	55	56	106	**111**
Bunch Intensity	10^{11}	0.7	0.7	0.7	0.9	**1.3**
Store Energy	GeV	100	100	100	100	**100**
$\beta*$	m	3	1	1	1	**1**
Peak Luminosity	$10^{30} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	2	6	6	10	**<u>35</u>**
Average Luminosity	$10^{30} \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1	4	4	6	**<u>20</u>**
Collision points	--	4	4	4	3	**2**
Time in store	%	30	41	38	56	**46**
Average Polarization, store	%	15	35	46	50	**<u>60</u>**

$$\mathrm{Stat.\,uncertainties} = 1 \Big/ \sqrt{Lum \cdot Pol^4}$$
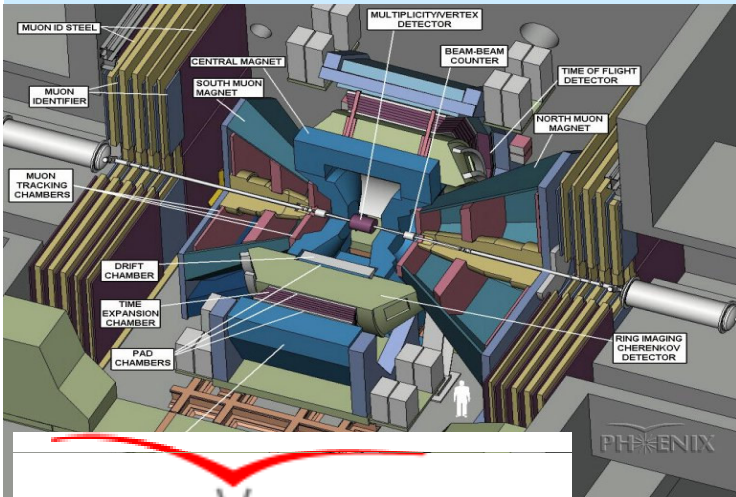
PHENIX and STAR

PHENIX:

High rate capability

High granularity

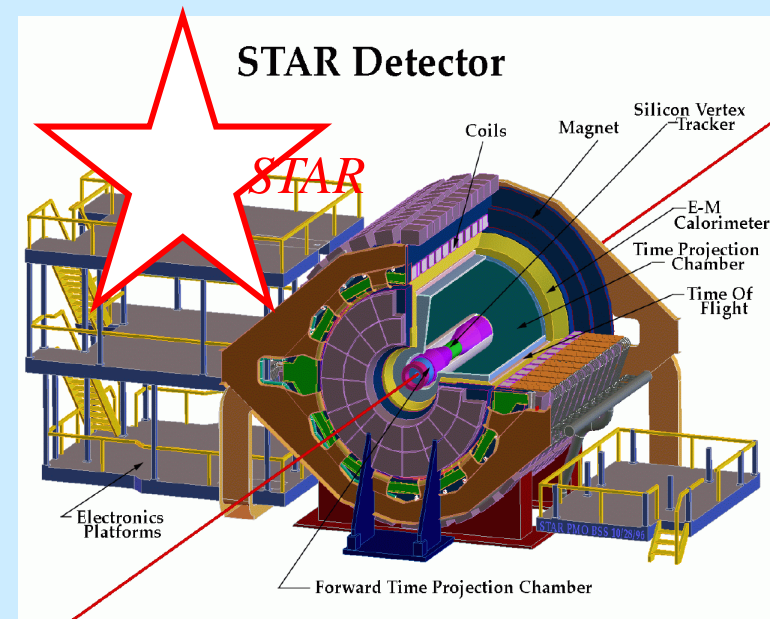**Good mass resolution and PID**

Limited acceptance

STAR:

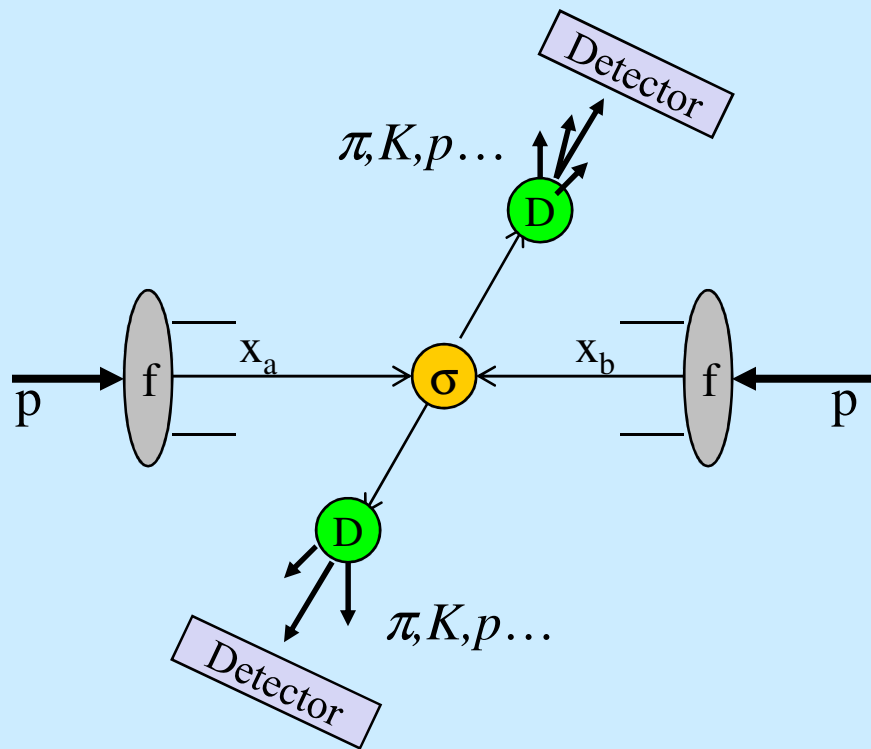**Large acceptance with azimuthal symmetry**

Good tracking and PID

Central and forward calorimetry

Observables

High Energy Proton scattering can be seen as a scattering of constituent partons: gg, qg, qq

Detector

$\pi,K,p…$

D

p $\rightarrow$ f $\xrightarrow{x_a}$ σ $\xleftarrow{x_b}$ f $\leftarrow$ p

D

$\pi,K,p…$

Detector

Quarks and gluons are not seen directly

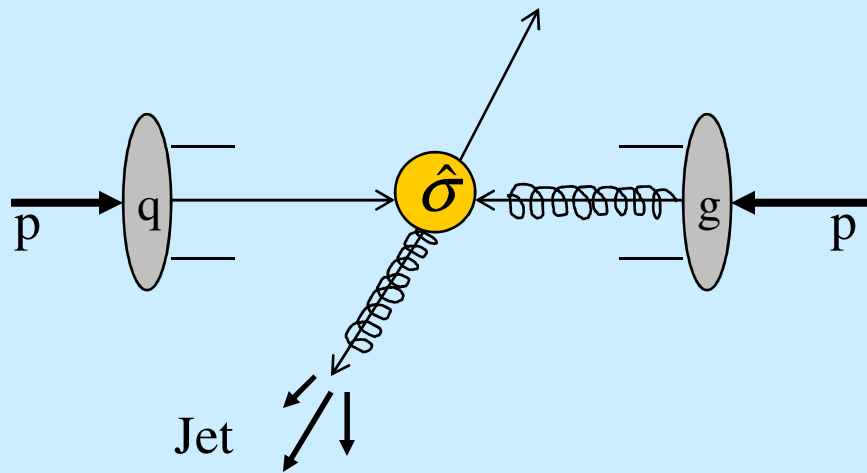They are locked within hadrons (confinement): baryons (protons, neutrons etc.) and mesons (pions, kaons etc)

Partons from hard scattering evolve via radiation and hadronization (fragmentation) processes to form "sprays" of nearly collinear hadrons - **Jet**

Observable:
   Either the whole **Jet** or its "fragments" (**hadrons**)
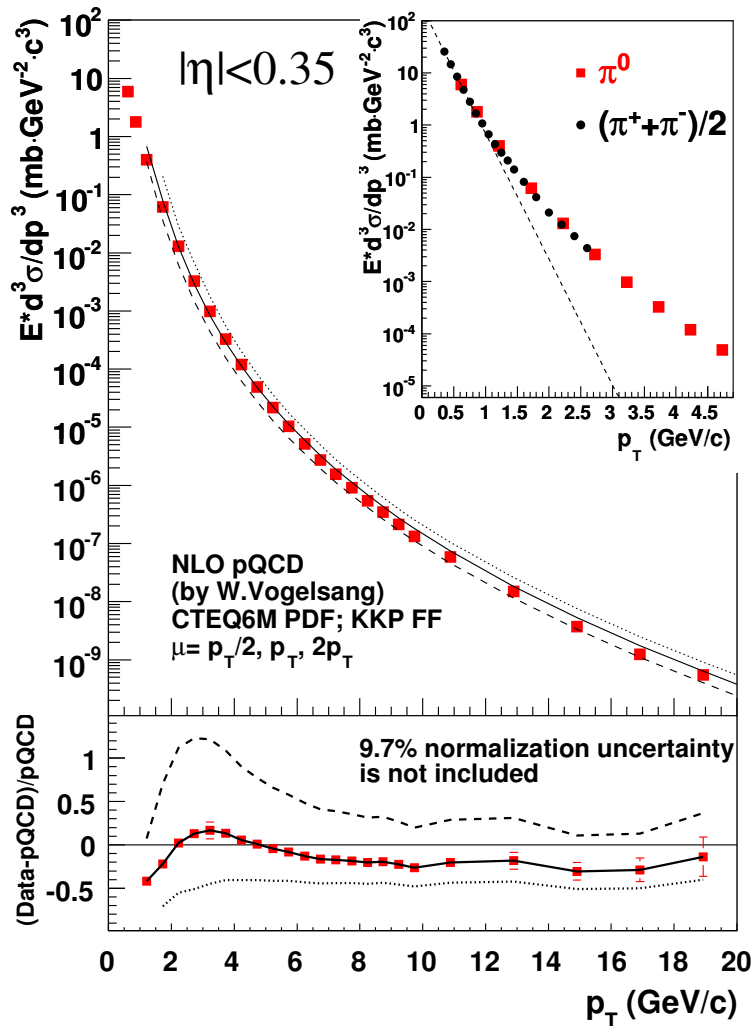
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RHIC Spin Measurements

Check theory (pQCD) works

This exp.   Other exp.   Theory

$$\text{Jet yield} = \boxed{q} \otimes \boxed{g} \otimes \boxed{\hat{\sigma}}$$

Extract polarized PDF from spin asymmetries using pQCD

This exp.   Other exp.   Theory

$$\text{Jet Yield Spin Asymmetry} = \boxed{\Delta q} \otimes \boxed{\Delta g} \otimes \boxed{\Delta \hat{\sigma}}$$

Extract!

Particle Yield in *pp*

$|\eta|<0.35$

π^0

$(\pi^+ + \pi^-)/2$

NLO pQCD
(by W.Vogelsang)
CTEQ6M PDF; KKP FF
$\mu = p_T/2,\ p_T,\ 2p_T$

9.7% normalization uncertainty
is not included

$E \cdot d^3\sigma/dp^3$ (mb·GeV^{-2}·c^3)

(Data-pQCD)/pQCD

p_T (GeV/c)

STAR (hep-ex/0608030)
p+p → jet + X
√s=200 GeV
midpoint-cone
r_{cone}=0.4
$0.2<\eta<0.8$

Combined MB
Combined HT
NLO QCD (Vogelsang)
NLO + Nonperturbative

Systematic uncertainty
Theory scale uncertainty

$1/2\pi\ d^2\sigma/(d\eta\,dp_T)$ [pb/GeV]

data / theory

p_T [GeV/c]

(a)

(b)
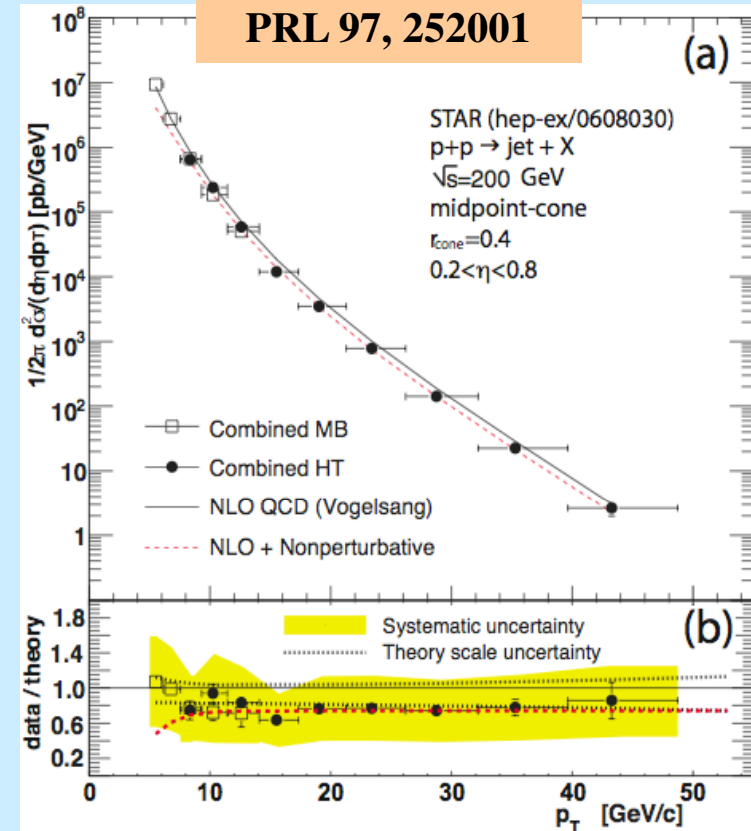
Good agreement between theory (pQCD) calculations and data ⇒ confirmation that pQCD can be used to extract spin dependent pdf's from RHIC data.
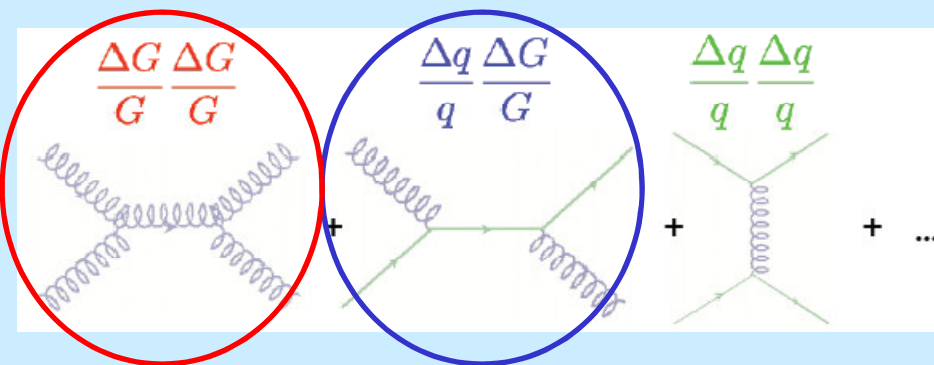
- Same comparison fails at lower energies

Probing ΔG in pol. pp collisions

$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

σ^{++} - particle production from beam with the same helicity

σ^{+-} - particle production from beam with the opposite helicity
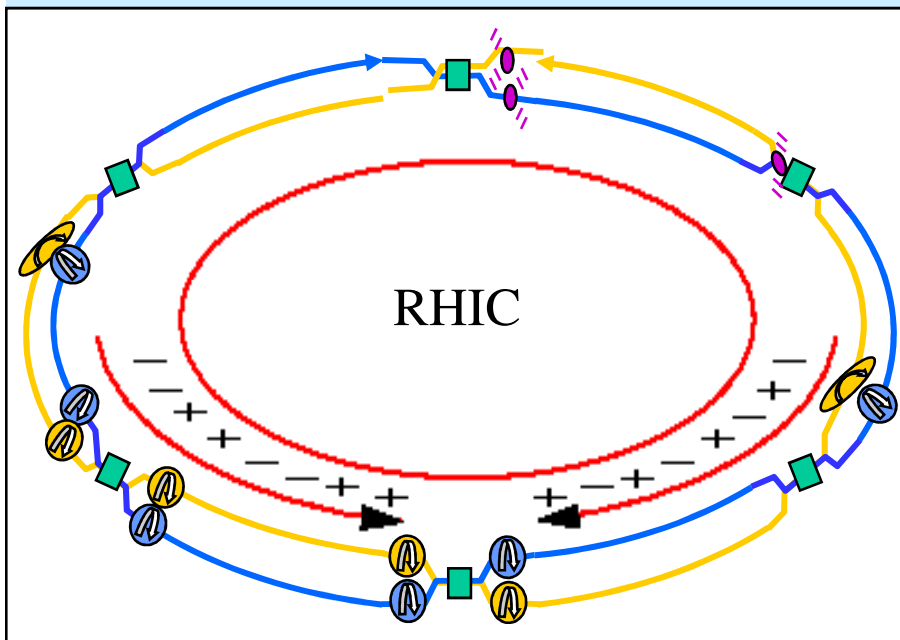
For inclusive Jet or hadron production:

Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

As a quadratic function

Measuring A_{LL}

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$

RHIC

(N) Yield

(R) Relative Luminosity
     (collision rate)

(P) Polarization

✓ Bunch spin configuration (+ or − helicity) alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time

$\Rightarrow$ Possibility for false asymmetries is greatly reduced

A_{LL}: jets

STAR Preliminary Run2006 ($\sqrt{s}$=200 GeV)

GRSV Models:

"$\Delta G = G$": $\Delta G(Q^2=1GeV^2)=1.9$

"$\Delta G = -G$": $\Delta G(Q^2=1GeV^2)=-1.8$

"$\Delta G = 0$": $\Delta G(Q^2=1GeV^2)=0.1$

"$\Delta G = std$": $\Delta G(Q^2=1GeV^2)=0.4$

Large and modest gluon polarization scenarios are not consistent with data
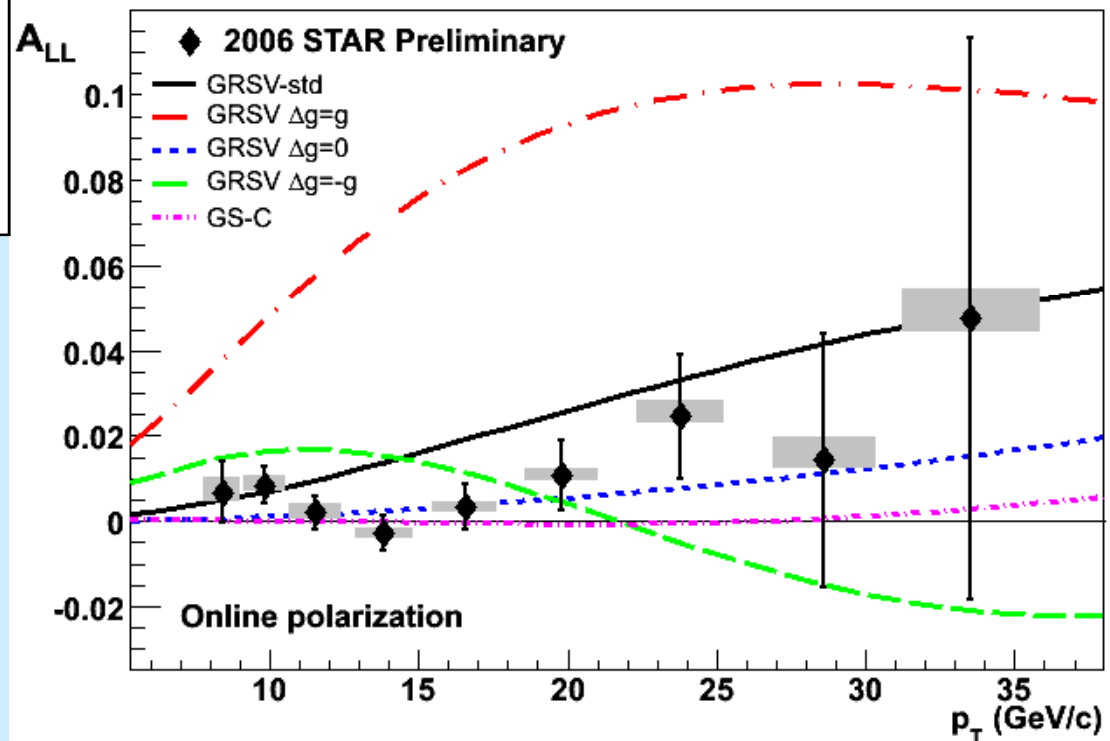
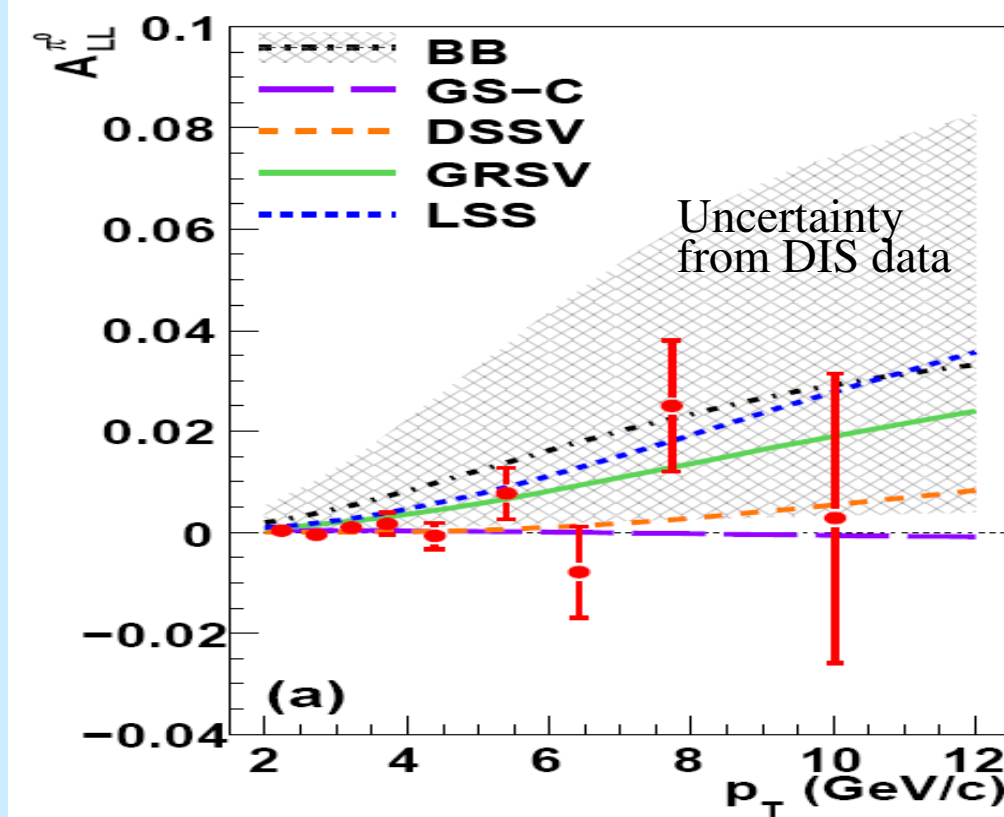Run2003&2004: PRL 97, 252001
Run2005: PRL 100, 232003

$A_{LL}: \pi 0$

Statistical precision of RHIC A_{LL} data started to dominate in ΔG constraint

Run3,4,5: PRL 93, 202002; PRD 73, 091102;
PRD 76, 051106 (R)

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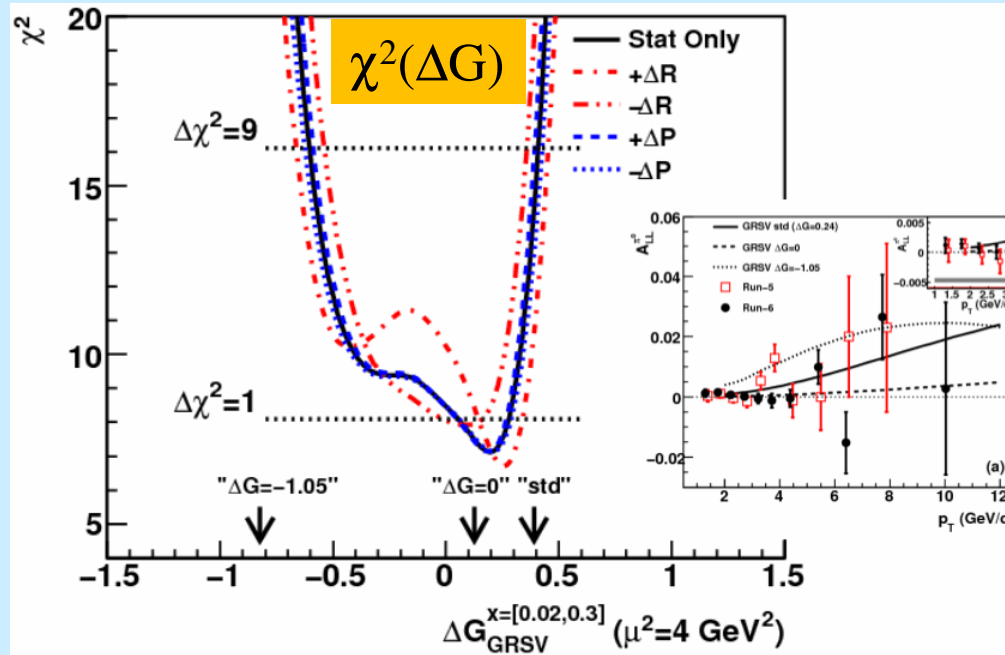# From $A_{LL}(p_T)$ to $\Delta g(x_{gluon})$

Generate $\Delta g(x)$ curves for different $\Delta G = \int_0^1 \Delta g(x)\,dx$

Calculate $A_{LL}(p_T)$ for each ΔG

Compare A_{LL} data to curves (produce χ^2 vs ΔG):

$$\chi^2 = \sum_{p_T\ bins} \frac{\left(A_{LL}^{data} - A_{LL}^{theory}\right)^2}{\sigma_{stat}^2}$$

From pQCD:

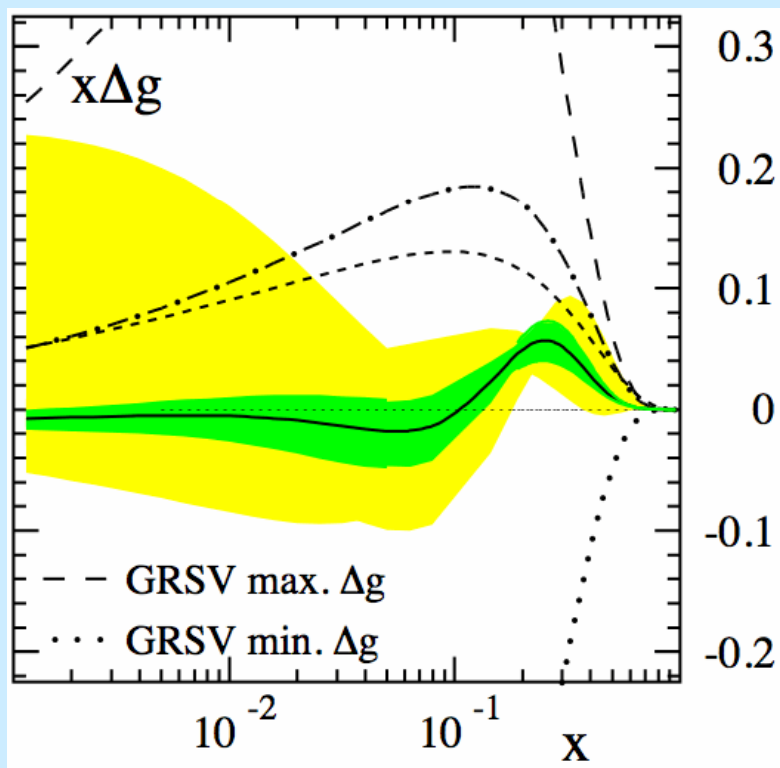$$p_T = 2-12\ \text{GeV/c} \;\rightarrow$$

$$x_{gluon} = 0.02 - 0.3$$

Stat. error : $\Delta G_{GRSV}^{x=[0.02,0.3]}\left(\mu^2 = 4\,GeV^2\right) = 0.2 \pm 0.1\ (1\sigma)$ and $0.2_{-0.8}^{+0.2}\ (3\sigma)$

Syst. exp. error : ± 0.1

ΔG: Global Fit

Daniel de Florian
Rodolfo Sassot
Marco Stratmann
Werner Vogelsang

- PRL 101, 072001(2008)
- First truly global analysis of polarized DIS, SIDIS and RHIC results
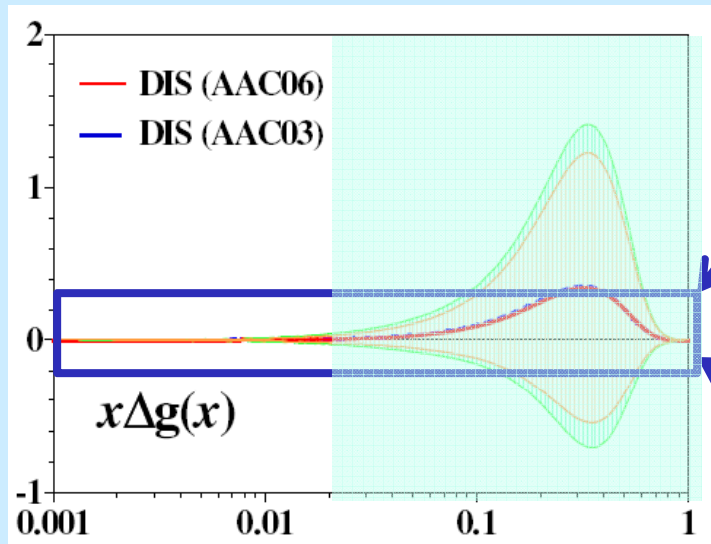

Uncertainty estimation:

$\Delta\chi^2=1$ (optimistic)

$\Delta\chi^2/\chi^2=2\%$ (conservative)

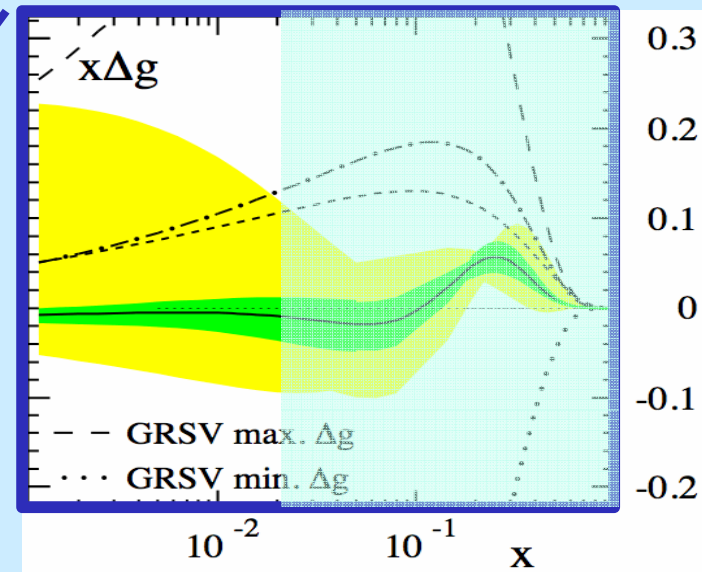… Truth is in between

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ΔG: From DIS to RHIC

DIS: AAC-2004

DIS+RHIC: DSSV-2008

RHIC data constrains ΔG at $0.02 < x < 0.3$

$\Delta G^{x>0.02} = 0.5 \pm 1.3$

$\Delta G^{x>0.02} = 0.0 \pm 0.1$ "Optimistic" error estimation: $\Delta\chi^2 = 1$

$\Delta G^{x>0.02} = 0.0^{+0.3}_{-0.2}$ "Conservative" error estimation: $\Delta\chi^2/\chi^2 = 2\%$

Considerable improvement in ΔG determination
(a lot of work still needed for correct error estimation)

So, the Proton Spin

Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

(Anti)quark Contribution: **0.10–0.15**

Gluon Contribution: **~0?**

Parton Orbital Momentum: **???**

Spin Crisis

Spin Crisis II?

Data are sensitive to $\Delta G = \int \Delta g(x)dx$ at 0.02<x<0.3
  Need to extend *x* range
  …Spin Crisis arose after getting access to lower x

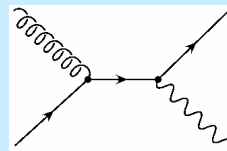Data are not sensitive to the shape of $\Delta g(x)$
  Need back-to-back processes

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ΔG at RHIC: what's next

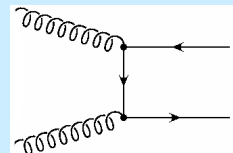❑ Improve exp. uncertainties and move to higher p_T (higher x)

❑ Different channels
  ✓ Different systematics
  ✓ Different x
  ✓ gq→gγ sensitive to ΔG sign

$$gq \rightarrow g\gamma$$

 $\propto \dfrac{\Delta q}{q} \dfrac{\Delta G}{G}$

$$gg \rightarrow Q\bar{Q}$$

 $\propto \dfrac{\Delta G}{G} \dfrac{\Delta G}{G}$

❑ *pp → γ + jet* and *pp → jet + jet*
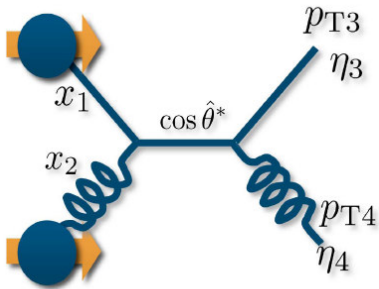 ✓ Map Δg vs x

❑ Different √s (colliding beam energy)
  ✓ Different x
  ✓ Important cross check: measurements for the same x at different Q^2

Improve exp. uncertainties

Need more FOM=P^4·L (stat. uncertainty ~ 1/√FOM)

A factor of 3-4 reduction in stat. errors
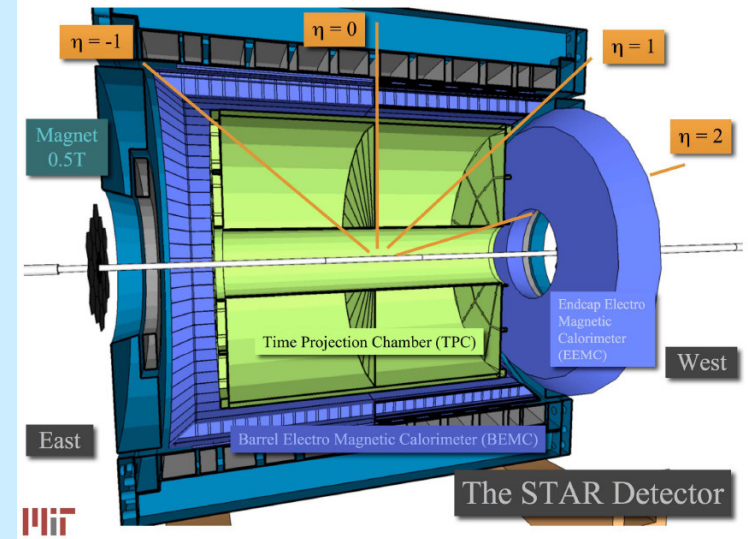expected in next √s=200 GeV RHIC Run
(2009 or 2010)
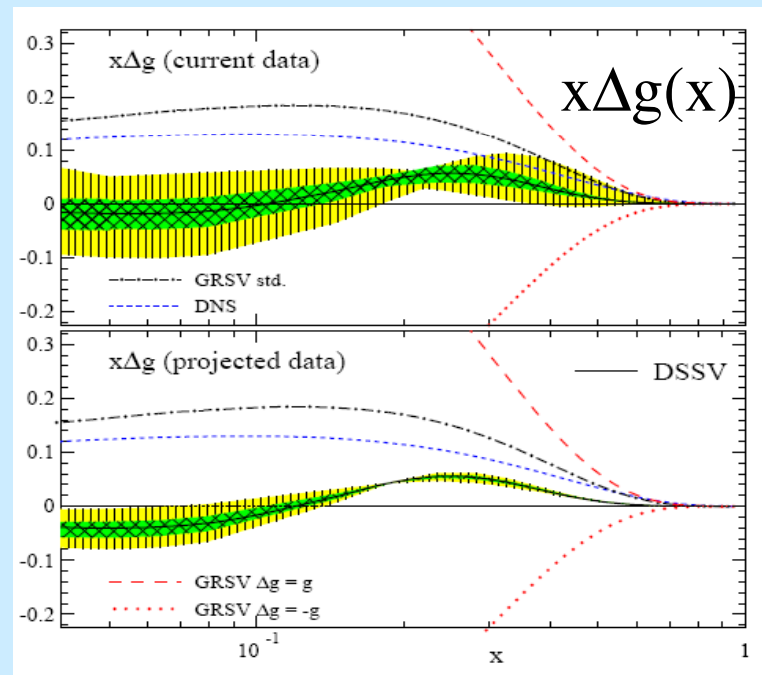
$$pp \rightarrow \text{jet} + \text{jet}$$

$$M_{Jet-Jet} = \sqrt{x_1 x_2 s}$$

$$\eta_3 + \eta_4 = \log \frac{x_1}{x_2}$$
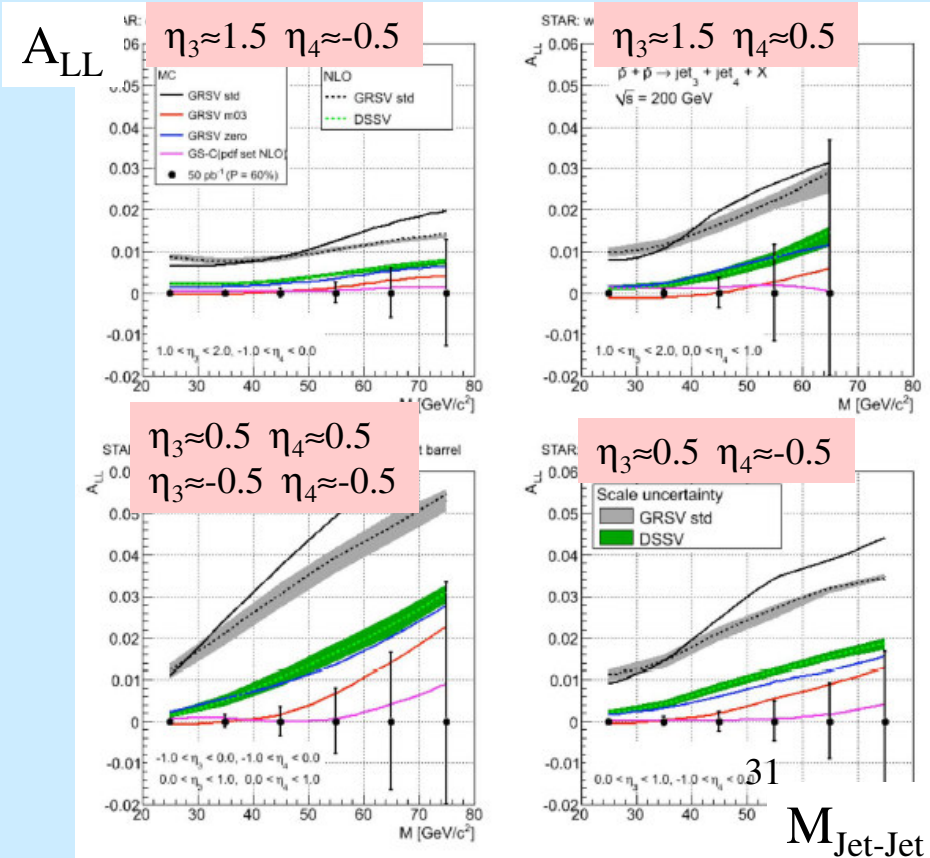
$$\eta = -\ln\left(\tan \frac{\Theta}{2} \right)$$

Parton kinematics (x_{gluon}) is well constrained

Sensitivity not only to the integral ΔG but also to the shape $\Delta g(x)$
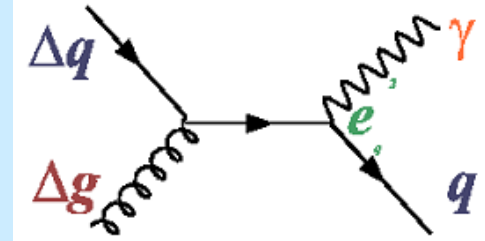
Better sensitivity to ΔG compared to inclusive jet measurements $pp \rightarrow \text{jet}+X$

Higher x asymmetries are not diluted by low x asymmetries as in inclusive measurements

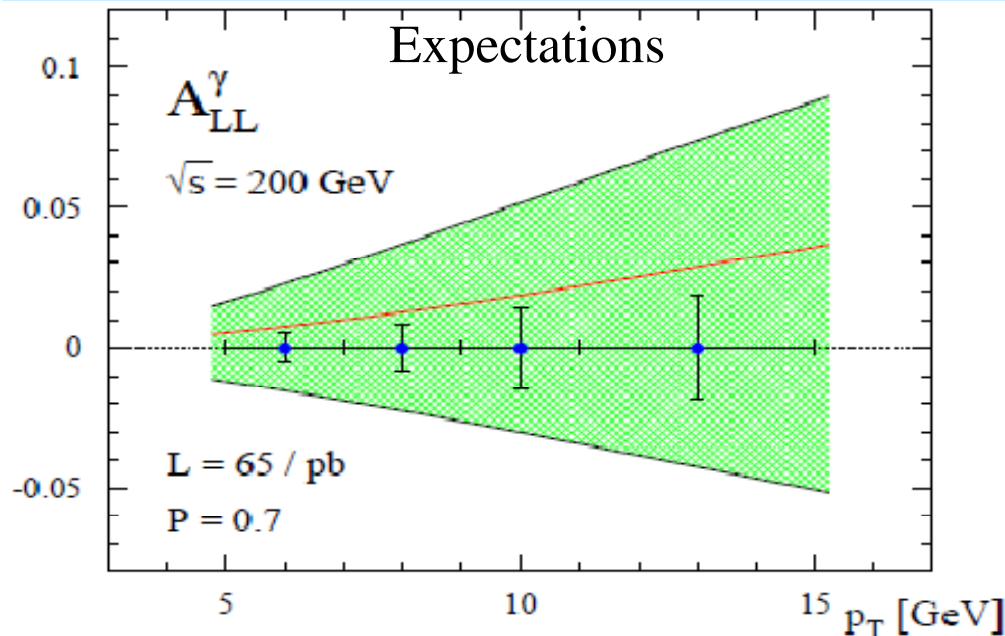More exclusive triggering (smaller background)

A_{LL}

$\eta_3 \approx 1.5 \quad \eta_4 \approx -0.5$

$\eta_3 \approx 1.5 \quad \eta_4 \approx 0.5$

$\eta_3 \approx 0.5 \quad \eta_4 \approx 0.5$
$\eta_3 \approx -0.5 \quad \eta_4 \approx -0.5$

$\eta_3 \approx 0.5 \quad \eta_4 \approx -0.5$

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$M_{Jet-Jet}$

$pp \rightarrow \gamma + X$

$$A_{LL} = \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\sum\limits_{i=u,d,s} e_i^2 \Delta q_i(x_2)}{\sum\limits_{i=u,d,s} e_i^2 q_i(x_2)} \otimes \widehat{\alpha}_{LL}(gq \rightarrow q\gamma)$$
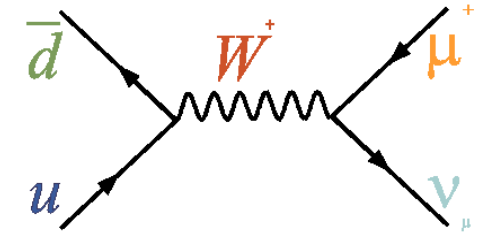
(Anti)quark polarization from DIS

Partonic level asymmetry from theory

Expectations

A_{LL}^{γ}

$\sqrt{s} = 200$ GeV

L = 65 / pb

P = 0.7

p_T [GeV]

Golden channel:

✓ Theoretically clean

✓ Small contamination (~15% from qq-bar annihilation

✓ Linear in $\Delta G \Rightarrow$ sign of ΔG

✓ Rare probe (needs a lot of luminosity)

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Flavor decomposition

$$\Delta d + \overline{u} \to W^{-}$$

$$\Delta \overline{u} + d \to W^{-}$$

$$\Delta \overline{d} + u \to W^{+}$$

$$\Delta u + \overline{d} \to W^{+}$$

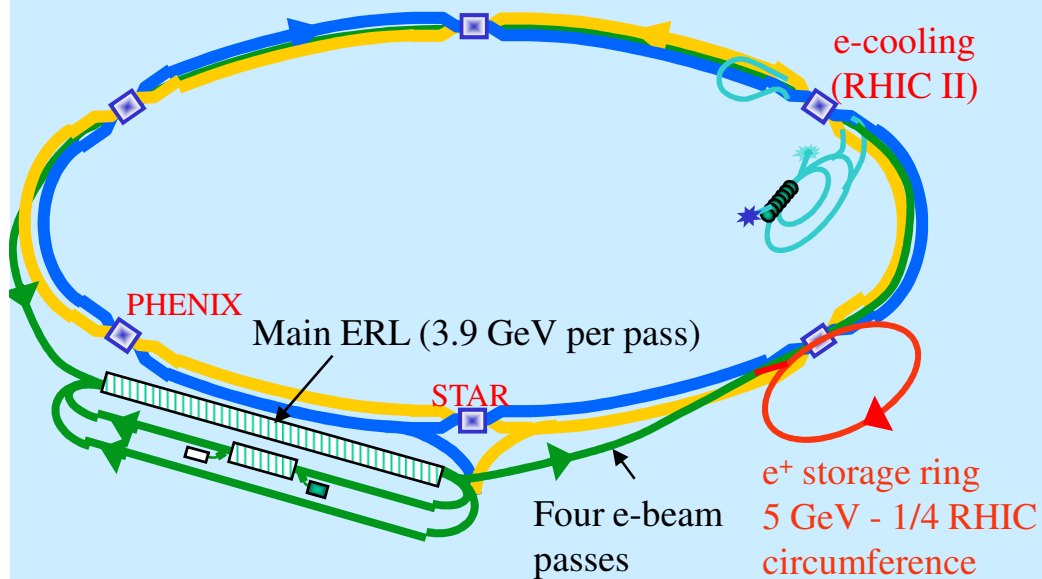Fixes (anti)quark flavor and its spin direction

Measured through longitudinal single spin asymmetry A_L in $W^{\pm}$ production at $\sqrt{s}$=500 GeV
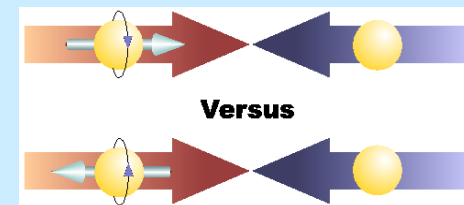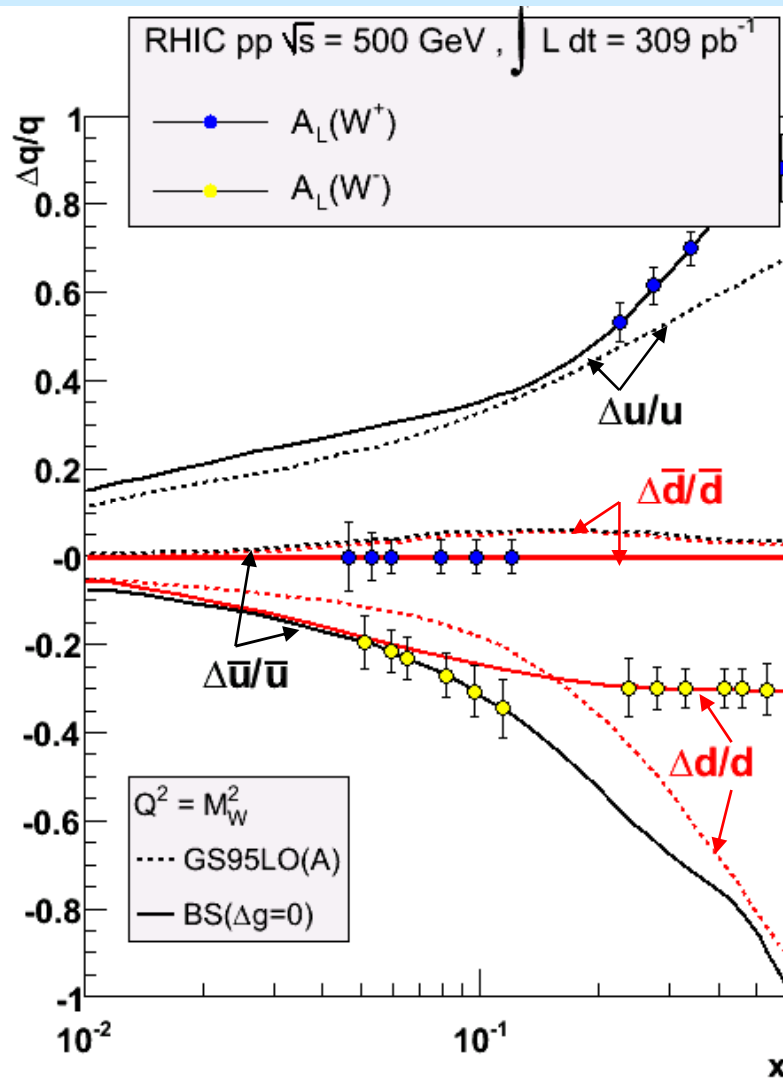
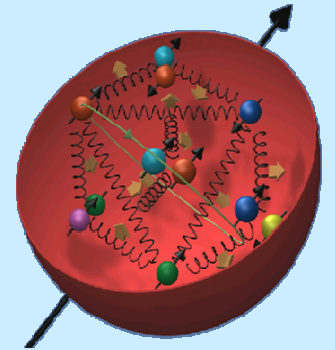**First data expected in a few weeks!**

eRHIC

Electron – Proton (and Ion) Collider

➢ Precise imaging gluon and sea quarks in the proton

➢ Get access to parton orbital momentum

➢ Electron energy range from 3 to 20 GeV
➢ Peak luminosity of 2.6×10^{33} cm^{-2}s$^-$
➢ High electron beam polarization (~80%)

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Summary

Proton Spin

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_z$$

(Anti)quark Contribution: 0.10–0.15
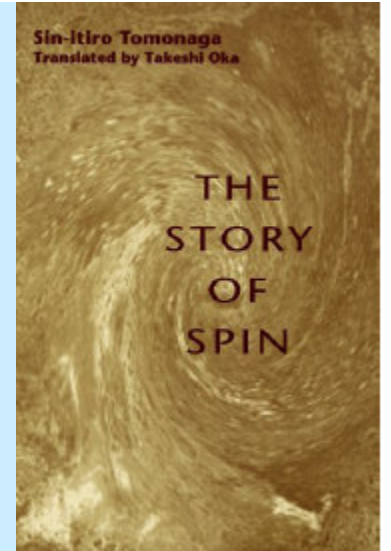
Gluon Contribution: ~0?

Parton Orbital Momentum: ???

**So, Do Gluons Carry Proton Spin? –
Current data indicate on small or zero contribution**

Higher precision and extended x range measurements of ΔG are necessary (RHIC, eRHIC etc.)

World wide quest in determining the parton orbital angular momentum contribution (JLab, eRHIC etc.)

The Story of Spin

Sin-Itiro Tomonaga

It is a mysterious beast, and yet its practical effect prevail the whole of science. The existence of spin, and statistics associated with it, is the most subtle and ingenious design of Nature – without it the whole universe would collapse.